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AN INVESTIGATION OF A DIRECT SIDE-FORCE MANEUVERING SYSTEM ON A DEFLECTED JET VTOL AIRCRAFT

by Terrell W. Feistel, Ronald M. Gerdes, and Emmett B. Fry

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Moffett Field, Calif.

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SUMMARY

A series of flight and simulator tests was conducted using the X-14A variable-stability jet VTOL research aircraft and an all-axis motion simulator to determine the acceptability of a direct side-force vane for sideward maneuvering without changing bank angle. The side-force vane, immersed in the jet exhaust of the X-14A just below the diverters, deflected the jet sideways through a small angle and was controlled by a device on the pilot's control stick, which could provide either proportional or on-off control.

The side-force vane with proportional control was evaluated in flight for the performance of lateral offset maneuvers of 1 to 2 wing-spans translation distance. For this task, the use of the vane for translation was preferred over roll when only a low value of roll-control power was available ($\ddot{\phi}_{max}$ = 0.6 rad/sec^2); with a higher control power available in roll ($\ddot{\phi}_{max}$ = 0.9 rad/sec^2) the two methods were equally acceptable. For the more complex task of maneuvering around a prescribed course, the direct side-force controller was not preferred because it introduced another pilot input into the system that had to be coordinated (in flat turns, etc.) and could be easily misapplied.

INTRODUCTION

The establishment of requirements for satisfactory hover control of VTOL aircraft has been the subject of many NASA flight investigations utilizing the variable-stability X-14A research aircraft (refs. 1 and 2). With the advent, in the near future, of VTOL aircraft in the 100,000-pound gross weight category, the need is emphasized to investigate all possible means of reducing control power requirements, especially in roll, to avoid an unnecessary performance penalty. One means of reducing the maneuvering control power requirement for a hovering vehicle, as distinguished from the trim requirement and the gust upset or disturbance requirement (ref. 3), is to provide a capability for wings-level translation and thus eliminate the necessity of rolling the

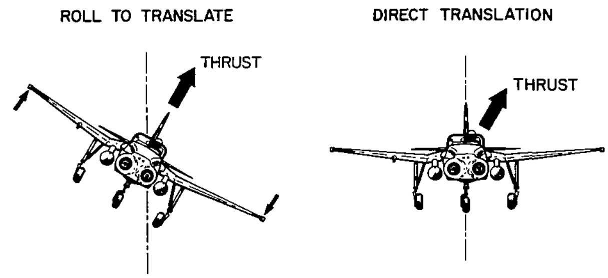

Figure 1.- Translational control methods, X-14A.

airplane to achieve a sideward thrust component (see fig. 1). The variable-stability X-14A, with a gross weight of approximately 4,000 pounds, was chosen for a preliminary flight evaluation of such a system because the airplane was readily available and relatively easy to modify for installation of a side-force vane in the exhaust. A multi-axis motion simulator was used also for a preliminary investigation and for the final selection of the control system.

NOTATION

DSF	direct side force
g	acceleration of gravity
Δa_y	incremental lateral acceleration, g
$\ddot{\phi}$	angular acceleration in roll, rad/sec^2

DESCRIPTION OF AIRCRAFT AND INSTALLATION

General

The X-14A is a deflected jet VTOL aircraft with a gross weight of approximately 4,000 pounds. It first flew in 1956 as the Bell X-14; since that time, GE J85-5 engines have been installed and a variable-stability system incorporated that allows variation of the control power and damping within moderately wide limits about all three axes. References 1 and 4 provide a more complete description of the aircraft and some results of earlier research into VTOL handling qualities. Figure 2 is a photograph of the aircraft in hovering flight; the inset shows the side-force vane installation in its final configuration.

Vane System Development

Figure 3 shows the steps in the development of the side-force vane to make it operationally useful. The original vane was of rectangular planform with a wedge-shaped cross section and a lateral planform area of approximately 0.9 ft^2. It was mounted between the two diverters and pivoted on a diagonal axis; a linear hydraulic cylinder activated the vane through a control horn.

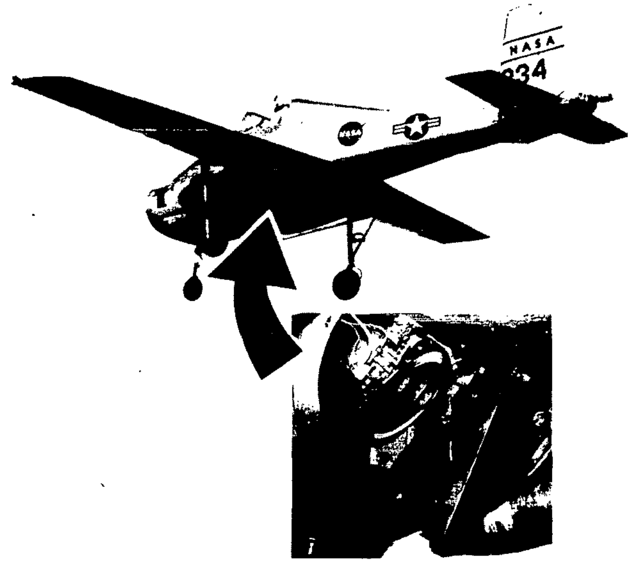

Figure 2.- X-14A VTOL aircraft equipped with lateral acceleration vane.

Figure 3.- Vane configuration development.

This installation was not integrated into the aircraft control system and was tested only briefly - first statically on a ground test stand, then in hovering flight at altitude. The maximum side force produced was insufficient to provide the 0.1 g lateral acceleration believed the minimum acceptable for evaluation as a maneuvering device. The deficiency was found to be due to the majority of the vane's surface being outside the main jet stream when the diverters were in the hover position. As shown in the figure, two triangular additions were made to the original vane, which converted it to a roughly trapezoidal planform and extended it into the mainstream of the jet, increasing its area by 75 percent. Flight tests with this configuration (in hover at altitude) showed that it produced nominally sufficient side force (about 0.09 g for 25° deflection). However, the diagonal (rather than horizontal) pivot axis of the vane resulted in an appreciable aft force (about 0.04 g for 25° deflection), which in one case resulted in a partial backward outside loop being performed unexpectedly. To avoid this difficulty, wing-like "outriggers" with airfoil cross sections were attached to the modified vane, centered in the jets. Their function was to reduce vane deflection angle for a given side force by using aerodynamic lift, as opposed to the simple flow deflection of the original configurations, and thereby to reduce considerably the aft component of force necessarily associated with a lateral deflection (approximately related to the tangent of the vane surface deflection angle).

Tests of this configuration (lower part of fig. 3) revealed that the nominal 0.1 g side force was attained at only about 12° vane deflection with 0.15 g available at approximately 18°. The undesirable

Figure 4.- Control stick grip for side-force vane actuation.

aft force was apparently eliminated completely and the appreciable rolling moment (approximately 0.2 rad/sec^2 for the nominal 12° deflection) was counteracted through the aircraft variable-stability system, which was programmed to provide an equivalent deflection of the servodriven roll nozzles in proportion to the vane deflection. The only remaining undesirable cross-coupling feature was a thrust decrement with vane deflection, which manifested itself when hovering with ground reference, as opposed to the earlier altitude hover check-out flights. This problem was found to be much less serious at deflections up to about 12° (corresponding to 0.1 g) than for the higher deflection (up to 18° or 0.15 g), which were not required for an operational evaluation of the vane system.

All these configurations featured a vane controller integrated into the aircraft control system through a device on the stick grip. Initially, this device was a self-centering, three-position switch (for on-off control); later a proportional "thumb cradle" controller with an appropriately modified stick grip was developed. Figure 4 shows this canted stick grip with integrated proportional thumb controller; its sensitivity was varied by adjusting a separate potentiometer on the instrument panel, which established the maximum vane deflection for full deflection of the controller.

RESULTS AND DISCUSSION

Simulation Studies

The simulation tests were conducted prior to the flight study to determine (1) a means of incorporating thrust-vectoring control into the basic aircraft control system (i.e., by a separate controller or with an interconnect from the conventional centerstick) and (2) the side-force authority required for satisfactory maneuvering. The investigations were performed with the Ames six-degree-of-freedom flight simulator (fig. 5). An additional function

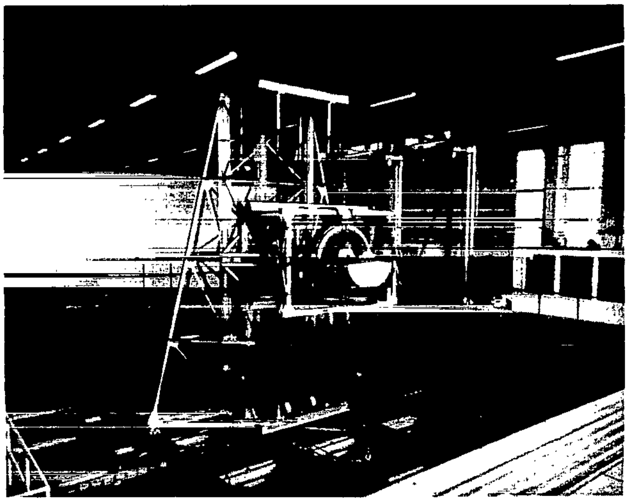

Figure 5.- Ames six-degree-of-freedom flight simulator.

of the simulator, which served to expedite the flight-test program, involved simulating the specific X-14A aircraft control system prior to flight test of each configuration.

Simulation.- The Ames six-degree-of-freedom flight simulator (described in more detail in ref. 5) has the capability of traversing a cube of space approximately 18 feet on a side. Within this limitation space is available to permit reproduction of all linear and angular motions of the X-14 without attenuation. Optimum side-force vane sensitivity and authority were then determined for certain maneuvers, based on the pilot's ability to control vehicle response as well as his comfort and feel.

The simulation tasks were comparable to the flight tasks in that the simulator was maneuvered laterally, as rapidly as possible, between styrofoam balls 18 feet apart (compared to 35 feet for flight). Gentle lateral maneuvering and simulated takeoffs and landings were also evaluated. All evaluations were made according to the Cooper Pilot Rating Scale in table I.

TABLE I.- NASA PILOT OPINION RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter.

Methods of side-force vane control.- Three methods of commanding side-force vane operation were studied in the simulator: (1) vane deflection proportional to control stick deflection, (2) vane deflection proportional to roll attitude, and (3) vane deflection commanded by separate thumb controller located on top of the center control stick, which was a rudimentary model of the device shown in figure 4.

In the first method, the vane was geared directly to the center control stick in combination with a basic rate-damped control system. Proper phasing was maintained between roll acceleration ($\ddot{\phi}$) and lateral acceleration (a_y), but no combination of side-force control parameters and basic roll-control system parameters could be found that did not introduce phasing problems between roll attitude and lateral acceleration. The phasing problem existed for the attitude-stabilized system as well, and this method of control was excluded from further study.

In the second method, side force was generated in proportion to bank angle with bank angle controlled by a rate-damped system. This method had the effect of increasing the sensitivity of side acceleration due to bank angle as seen in the expression

$$a_y = K(g \sin \phi)$$

where K is normally equal to unity. Gains up to K = 1.5 were considered helpful, but at higher gains the tendency of the pilot to overcontrol began to degrade the system excessively.

For the third method, two types of thumb controller action, on-off and proportional, were studied. (A first-order time constant of 0.2 sec was used to approximate system response.) The proportional thumb controller was preferred because of the pilot's desire to modulate side acceleration for precise control. The proportional system also permitted slightly higher control authority to be utilized comfortably by a more gentle initial onset of acceleration.

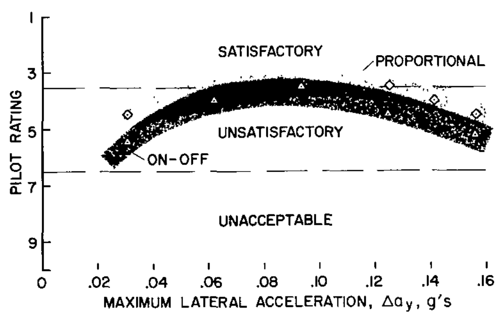

Figure 6.- Effect of lateral acceleration on pilot rating for two types of thumb controllers, six-degree simulator.

Effect of side-acceleration authority.- The project pilot studied the effect of varying control authority of the proportional and on-off thumb controllers in the simulation while performing the test maneuvers. All simulator motions were operated except roll angular motions, which were switched off to simulate idealized attitude stability. The results are shown in figure 6. A minimum authority of about 0.08 g was required to satisfactorily perform the simulation tasks, while anything above 0.13 g tended to be uncomfortably jerky. This jerkiness was caused by high-frequency resonance of the simulator structure, and the degradation in pilot rating at high values of Δa_y was not present in the flight data.

Effect of method of control and maximum roll-control power.- For these tests, roll-attitude control was achieved by a rate-damped control system with optimized characteristics as described in reference 5. The proportional thumb controller and side force proportional to bank-angle systems were evaluated, using the best control authority gain as determined from the previously described tests, while roll-control power ($\ddot{\phi}$) was decreased incrementally to a very low value. Comparison was then made with the conventional roll-to-translate method of control to determine the roll-control-power reduction made possible by use of the side-force vane systems. The results are presented in figure 7, and three conclusions are evident: (1) Both vane systems were superior to the conventional rate-damped control system at low values of control power. (2) The vane controlled from a proportional thumb controller mounted on the normal control stick was the best system tested. (3) None of the systems tested provided really outstanding performance (pilot ratings < 3).

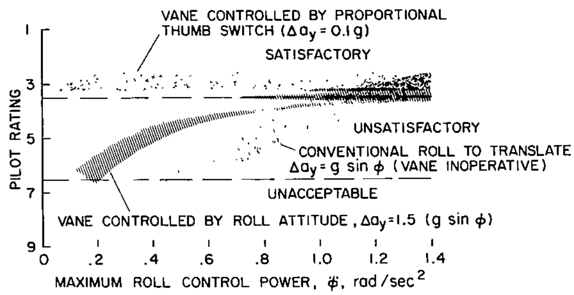

Figure 7.- Effect of various lateral translation methods on pilot rating, six-degree simulator.

The method of coupling vane deflection with bank angle had the obvious benefit of requiring less angular displacement and hence lower maximum $\ddot{\phi}$ to achieve a given lateral acceleration. While this system was superior to the conventional system at low values of $\ddot{\phi}$, as shown in figure 7, the pilots objected to its high sensitivity to small disturbances in roll. This "skitterish" characteristic made it slightly less desirable than the conventional system at values of $\ddot{\phi}$ of approximately 1.4 rad/sec^2.

The separate thumb controller was clearly easier to use for lateral maneuvering, and the pilot needed only sufficient $\ddot{\phi}$ control to overcome inadvertent upsets. The pilot desired attitude stabilization in roll, which would virtually eliminate any requirement for additional roll control.

Flight-Test Evaluation

Control power study.- A simple maneuver - a hovering translation laterally between two points - was chosen for the initial evaluation of the direct side-force controller in flight. This also was believed to be the minimal lateral maneuvering requirement for a large VTOL transport. For the X-14A, the translation distance was chosen in terms of wing spans to allow a degree of normalization. Translations were made between reference markers (visible in the photograph in fig. 11), 1 and 2 wing spans apart (corresponding to 35 and 70 feet, respectively), at a wheel height of 15 to 20 feet (high enough to avoid ground effects, yet low enough for hovering ground awareness). Variation of maximum side-force capability and translation with varying roll-control power (as compared to translation with a nominal, approximately 0.1 g maximum, side-force capability) were investigated.

Figure 8 shows the pilot ratings (based on the Cooper Scale, table I) of the control power available in roll for the performance of this simple lateral

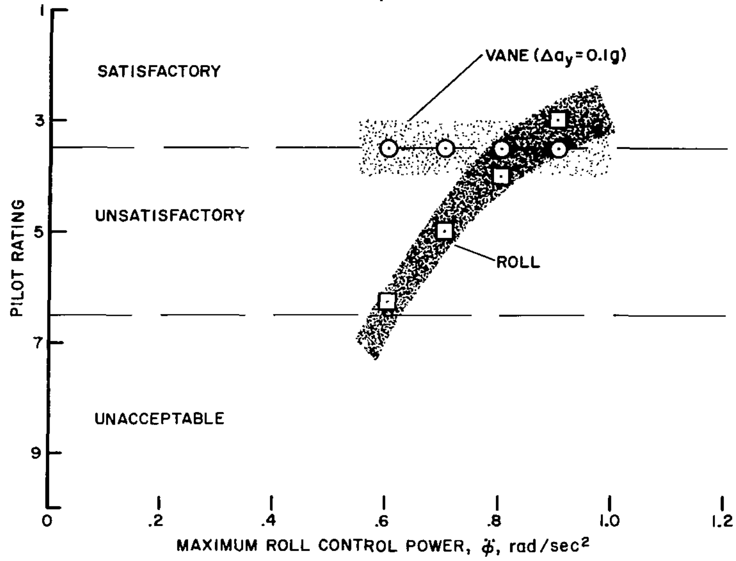

Figure 8.- Comparison of vane translation and conventional roll control methods for lateral maneuvering, X-14A.

offset maneuver in hover. The upper curve shows the effect on pilot rating of a variation of rolling acceleration capability (roll-control power) when the side-force vane (with a nominal 0.1 g maximum acceleration capability) is used to translate. The lower curve shows the effect on pilot rating of varying the roll-control power when translation is accomplished conventionally (by rolling). It can be seen that the two curves cross at a maximum rolling acceleration capability of about 0.9 rad/sec^2 (corresponding to a marginally satisfactory pilot rating of 3-1/2); below this value, the roll mode is progressively less preferable until, at approximately 0.6 rad/sec^2, the airplane becomes only marginally acceptable (pilot rating of 6-1/2) for the conventional performance of this maneuver. As angular acceleration was reduced for the conventional (roll to translate) method of control, the airplane became too sluggish and the pilot used full control to speed up repositioning. Consequently, pilot rating deteriorated because no control margin was available for correcting trim or upsets. These flight results confirm the simulator tests in that less maximum angular acceleration was needed to obtain a satisfactory pilot rating when the vane was used to reposition the aircraft laterally.

An interesting point is the lack of variation of pilot rating with roll-control power when the direct side-force control is used for translating. This mode was considered marginally satisfactory (PR = 3-1/2), irrespective of roll-control power, down to the 0.6 rad/sec^2 felt to be the minimum for prudent flight testing of this airplane. It should be noted that these data represent an ideal hovering condition for this system (i.e., in calm air, out of ground effect) and were taken to more nearly represent an aircraft with automatic attitude control (as would probably be used in a large VTOL vehicle, see ref. 5). These pilot ratings are not to be directly compared with those in reference 1 which take wind and ground effect disturbances into account.

The increment in control power ($\ddot{\phi}$ = 0.3 rad/sec^2) between the level for marginally acceptable maneuvering in roll ($\ddot{\phi}$ = 0.6 rad/sec^2) and that which is marginally satisfactory ($\ddot{\phi}$ = 0.9 rad/sec^2), is significant in that it approximates the minimum maneuvering-control-power requirement in roll for this particular aircraft and flight condition. This is to be distinguished from the requirements for the basic aircraft self-disturbance effects and for gust and outside disturbances (see ref. 4) which should be approximately represented here by the minimum control power required for steady hovering with no maneuvers (0.6 rad/sec^2).

Effect of varying vane authority.- Another series of flight tests was conducted to determine the amount of side acceleration desired for wings-level lateral offset maneuvers. The results (fig. 9) indicate that Δa_y of the

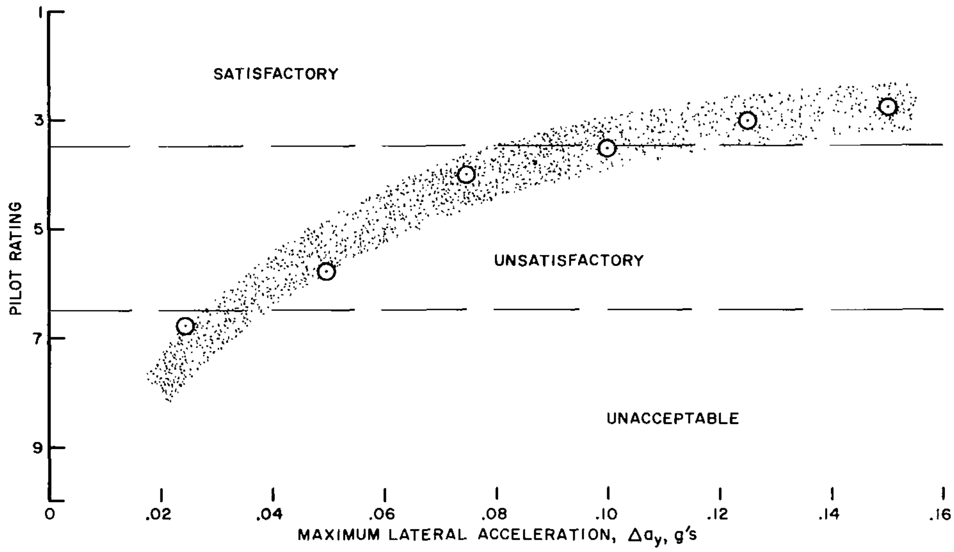

Figure 9.- Effect of lateral acceleration on pilot rating, X-14A.

order of 0.03 g is acceptable and 0.10 g is satisfactory. In terms of the amount of time required to move sideward 1 wing span, the foregoing Δa_y values correspond to approximately 13 and 7 seconds, respectively. When low values of Δa_y were used, the response was too sluggish and too much lead time was required to maneuver precisely.

More general hovering task.- To investigate the utility of the vane for a more complex task, an obstacle course was set up on the ramp (fig. 10). Flights around this course revealed that higher values of Δa_y (> 0.10 g) were desired when moving forward as well as sideways. In flat turns, however, at around 20 knots forward speed, the maximum side-force capability of the vane (0.15 g) was insufficient to offset the centrifugal force and the pilot preferred to add bank angle. At high Δa_y values, there was an appreciable thrust decrement and a consequent loss of altitude, which necessitated adaptation by the pilot.

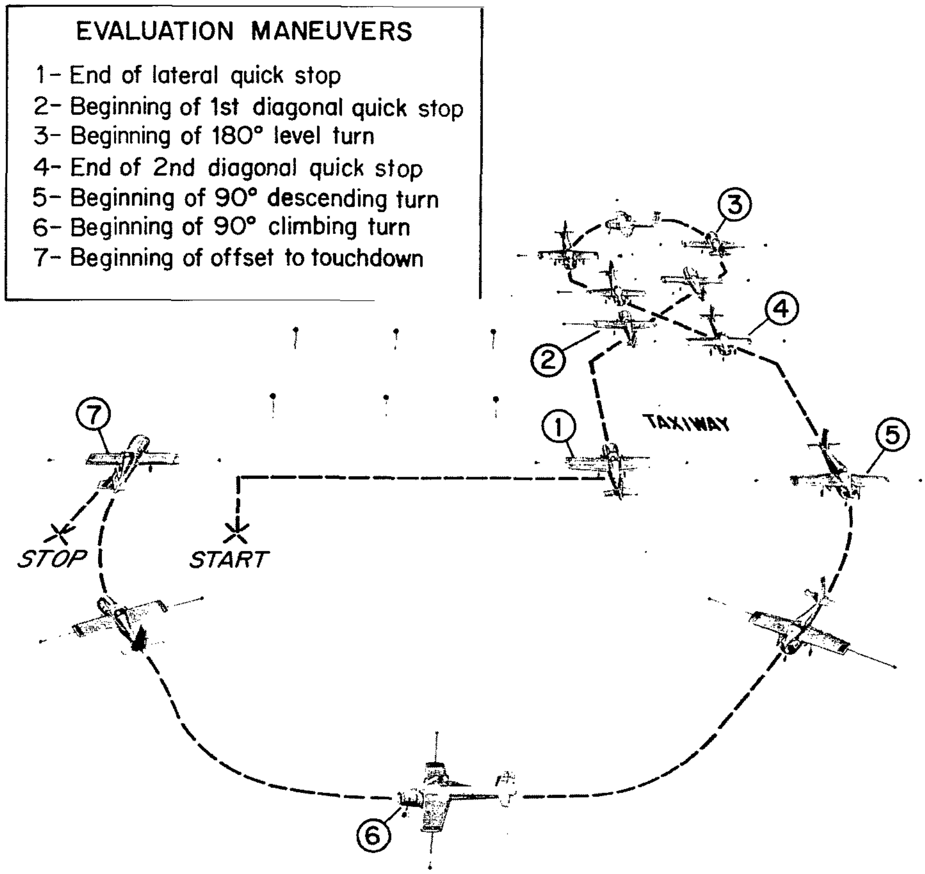

Figure 10.- Diagram of flight ramp evaluation course.

Use of vectored thrust for larger aircraft.- The limited tests on the X-14A allowed only speculation on the acceptability of a lateral acceleration device for larger aircraft. Therefore, to simulate a larger craft, the apparent wing span of the X-14A was doubled (fig. 11) by installing lightweight tubes and wing tips of orange styrofoam spheres. Three pilots then evaluated the thrust vectoring control as well as the conventional roll-to-translate method for the extended span aircraft in air-taxiing quick reversals and obstacle course maneuvers. Although there was a barely perceptible tendency to hover at a higher altitude, none of the pilots preferred to use thrust vectoring to avoid hitting a wing tip in these operational maneuvers. Although the tests generally uncovered no serious limitations to the use of the vane control for larger aircraft, the pilots felt that this type of control would be more preferable for air-taxi-type maneuvers (slow, relatively short distances) in which, for quicker repositioning, the pilot would prefer to realine the aircraft in a flat turn.

The flat-turn maneuver requires training because the lateral accelerations are not natural. Further research should be conducted with the vane control in slow-speed flight; however, as noted previously, attitude

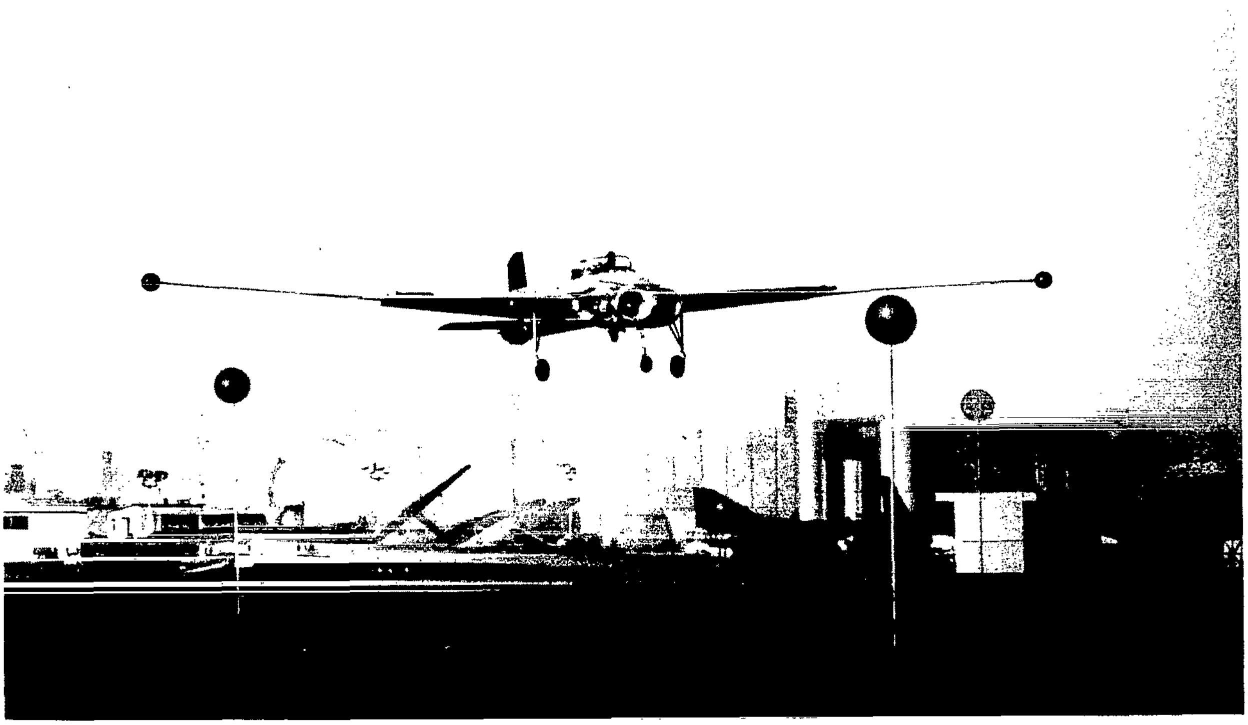

Figure 11.- X-14A VTOL aircraft with wing extensions.

stabilization is needed to unburden the pilot and allow a more accurate assessment of the vane control method.

PILOT COMMENTS

The following qualitative remarks are based on 13 altitude hover (2500 ft) and 30 ramp hover flights.

Cockpit Controls

A control-stick mounted thumb-activated switch was found suitable for direct side-force (DSF) control inputs. Stick grip geometry was such that the thumb had to be rested on the vane controller at all times (fig. 4). Thus, breakout force and deadband characteristics had to be tailored high enough to prevent inadvertent DSF vane inputs during stick maneuver inputs and yet low enough to be suitable for continuous vane hover maneuvering operations. The stick grip mounting angle also required readjustment to allow for a more comfortable positioning of the thumb on the vane control switch. In addition, it was found that any requirement to hold out-of-trim forces on the control stick reduced the vane controller "feel" and vane maneuver precision.

Aircraft Lateral Displacement Response Characteristics

On-off control.- On-off control was found generally unsatisfactory. If high DSF control powers were selected, the step response of the vane was uncomfortably jerky and led to a degree of overcontrol. The induced rolling moment due to vane deflection (roll coupling) further aggravated this situation. When DSF control power was reduced, response was sluggish and incorporation of other controller inputs appeared necessary.

Proportional control without roll decouple.- Incorporation of proportional control permitted effective use of higher DSF control powers. Lateral jerkiness was reduced, and roll-coupling moments could be counteracted with greater precision but they were still very bothersome.

Proportional control with roll decouple.- DSF control powers above 0.1 g were considered satisfactory. The manner in which the controller inputs were applied was a function of DSF control power. That is, proportional control inputs were used exclusively when control power values were above 0.1 g, while on-off control techniques (from stop to stop) were employed with control powers below about 0.07 g. Controller sensitivity about the neutral point initially was a problem in the range above 0.1 g. It is believed that use of a nonlinear controller would have improved the sensitivity characteristics. It was found that satisfactory DSF lateral quick-stop maneuvers could be performed with roll-control power set at a very low $\ddot{\phi}_{max} = 0.6$ value. This, of course, only indicates that DSF can be used in place of roll attitude changes for lateral translation and thus minimizes the overall roll-control power required for maneuvering in hover. However, it was felt that roll-attitude stability should have been incorporated to reduce pilot workload.

Other cross-coupling effects.- A slight amount of yaw (into the direction of applied side force) was noted on several occasions, but was never positively identified. Loss of lift at large vane deflections was quite pronounced. Lift loss might very well be a factor in defining the upper limit of satisfactory DSF control power. Any cross-coupling effects induced by DSF control inputs should be removed if DSF is to be an effective and desirable method of translating laterally. Such effects only add to the pilot workload.

Aircraft Multiaxis Response

DSF/height control.- A two-axis task, requiring coordinated use of DSF control and thrust changes for height control, involved a lateral offset maneuver, and deceleration to a preselected touchdown point (fig. 10). Lift loss due to vane deflection added to the height control task. Generally speaking, coordination of DSF and height control inputs was found to be satisfactory after a short practice session to determine lift loss effects.

DSF/pitch control.- A constant heading accompanied by a 45° change in ground track during air taxi was used to evaluate two-axis coordination of DSF and pitch attitude for speed control (see fig. 10). There was a natural tendency to use roll attitude changes to achieve lateral velocity rather than vane displacements. This tendency is believed to be due primarily to lack of artificial attitude stability.

Wings-level turns.- Flat turns were made to evaluate three-axis coordination of DSF, pitch attitude, and yaw rate controls (fig. 10). These turns required the greatest learning time. There was a tendency to let the nose come up, which resulted in a decrease in ground speed. Reference to sideslip information was required for coordinated yaw rate inputs at zero sideslip angle. This would be most important in aircraft with high roll due to side velocity. Uncoordinated turns were uncomfortable and required time to develop proficiency. Once more, there was a tendency to use roll attitude to "help the turn along." Minimum turning radius was a limitation since it is a function of DSF at any given ground speed.

Total pattern evaluation.- Several practice evaluation maneuver patterns were flown in a UH-12E helicopter for subsequent comparison. Average time around the course was about 90 seconds. Times for the X-14A were 70 to 80 seconds using roll attitude and 80 to 90 seconds using DSF. Pattern velocities achieved in the X-14A were as high as 25 knots forward and 20 knots sideward. There was no advantage in using DSF from a minimum time standpoint during this task. Furthermore, DSF control was not preferred over conventional roll attitude control for the following reasons: (1) Without automatic attitude stabilization, the pilot must still control attitude to compensate for aerodynamic and exhaust wake (ground effect) disturbances inherent in the X-14A. (2) Pilot workload is also increased because of additional (DSF) control tasks that must be coordinated with primary control inputs.

Size effects.- There was little concern about striking the ground with the wing-tip extensions during roll-attitude-controlled lateral quick stops while hovering out of ground effect (15-20 ft). Wing-tip clearance was not a problem, and thus, from the pilot's standpoint, there was no apparent advantage for a larger aircraft in maneuvering with DSF control as compared to using roll attitude changes.

CONCLUDING REMARKS

A flight test and simulator program has investigated the utility of a direct side-force maneuvering device for a VTOL aircraft in hover. The aircraft used was the X-14A, deflected jet VTOL with variable-stability provisions. A side-force vane installed in the jet exhaust was deflected through a thumb controller on the pilot stick. The side-force vane was initially evaluated for the performance of lateral offset maneuvers of 1 to 2 wing-spans translation distance. For this simple task, the use of a proportionally controlled vane for translation was preferable to using roll with low roll-control power ($\ddot{\phi}_{max}$ = 0.6 rad/sec^2). With higher roll-control power available ($\ddot{\phi}_{max}$ = 0.9 rad/sec^2), the two methods were equally acceptable. For the more complex task of maneuvering around a prescribed course on the ramp, the direct side-force controller was not preferred as it introduced an additional control variable that had to be coordinated (in flat turns, etc.) and could be easily misapplied. On the basis of pilot opinion, a side-force controller in an attitude-stabilized aircraft would be more satisfactory since the control task would be considerably simplified.

Another part of the investigation involved the installation of extensions on the wings to effectively double the apparent wing span and thus allow the cursory simulation of a large VTOL aircraft and directly explore the anticipated advantage of direct lateral acceleration capability when the desire or tendency to bank is physically or psychologically impeded. None of the test pilots could perceive any effect of the increased span, per se, on their tendency to bank during hovering maneuvers around the ramp or in their method of flying the airplane in general.

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National Aeronautics and Space Administration
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